

# Geometrical parametrization of warps for edge-on galaxies

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## 1. Introduction

The warp of most discs of spiral galaxies is at present a controversial dynamic phenomenon. Current hypotheses have been reviewed by Binney (1992), Combes (1994) and Battaner (1995). From the observational point of view a statistical analysis is at present lacking. Some works have been reported dealing with the statistics of warps, such as those by Bosma (1991), Briggs (1990) and Christodoulou et al. (1993). But these works consider a small sample of 21 cm mapped galaxies, mainly because few galaxies at present have available 21 cm maps. These galaxies have been studied in considerable detail, on the other hand. Warps are worse observed in the optical, but the available sample is bigger. Statistical analysis of optical warps has been carried out by Sánchez-Saavedra, Battaner and Florido (1990) and Reshetnikov (1995). However there are at present large quantities of data, in particular the *Digitalized Sky Survey*, which could allow these works to be greatly extended.

With this purpose, it would be convenient to develop software to automatically characterize the basic properties of warps, avoiding subjective appreciations, and to define some parameters accounting for the basic description of each warp. The number of these parameters should be kept small, whilst retaining a geometrical description as complete as possible. We introduce here a *warp parameter*, accounting for the degree of warping, and three fitting parameters for the warp curve.

We also describe here the software developed to obtain these parameters. This software, called WIG (Warps in Inclined Galaxies) precisely determines the centre and the position angle of the galaxy, cleans the image from nearby stars, calculates the centroid curve and determines the value of the above-mentioned warp parameters.

We show examples of the application of WIG to different edge-on galaxies observed at different wavelengths. In the optical (I band), we study the galaxy ESO 235-53, which exhibits a clear warp, using the data from de Grijs (1997). The warp of this galaxy has been studied in detail by de Grijs (1997). In 21 cm we examine the well known warp of NGC 4013 (one of the most representative warped spirals) using the data from Bottema (1995). We also study the galaxy NGC 4565 as it has been observed in the mm continuum by Neininger and Guelin (1995), whose emission is mainly produced by dust, and which represents a very interesting new tool to study warps, as well as other dynamic features of galaxies.



## 2. The warp parameters

The warp of a galactic disc is a global property of the galaxy, and so, its measurement should not be affected by the internal details. Therefore, it is convenient to have a simplification of the galactic geometry which allows us to study global geometric properties. With this purpose in mind we construct what we call the *warp curve*. When studying the warp for an edge-on galaxy, we are interested in two directions contained in the plane of the sky: the direction defined by the major axis of the galaxy and the direction of the rotation axis of the galaxy. Throughout this paper we will identify the former with the  $x$  direction and the latter with the  $y$  direction, taking the centre of the galaxy as the origin of coordinates. Then, the *warp curve* is defined as the locus of points  $x_i, y_i$  which tells us the deviation with respect to the symmetry plane of a point at a given distance from the galactic centre. The warp curve represents just the warp when the galaxy is projected in the plane of the sky, and cannot account for effects such as the twist of the line of nodes. Bottema (1996) also suggests that a corrugated dust lane can mimic the presence of a warp. However, it is not known whether an external corrugation and a warp are different phenomena from a kinetic point of view. There are also other, lesser, difficulties of interpretation. Nevertheless, the warp curve is an adequate description of the geometry of the projected warp, and therefore, we will take it as the starting point in the definition of the geometrical parameters.

A galaxy is said to be more warped than another if the *deviation* of its *outer* part with respect to the plane of symmetry is greater. According to this concept, and taking into account the previously defined axis, a parameter which is intended to account for the warp should be proportional to the  $y$  coordinate of all points in the warp curve. On the other hand, the warp is a peripheral phenomenon, and therefore, the outer points should have a greater weight when measuring the warp. A properly defined “warp parameter” should match the following properties:

- a) It should be non-dimensional, to assure its value does not depend on the chosen units (pixels, arcsec, etc...)
- b) It should not depend on the galaxy size (only on its shape)
- c) It should not depend on the angular resolution of the image (even if a better resolution would provide a more precise evaluation).

The continuous form of the definition should be  $\int y dx$ , or better, to get a non-dimensional expression, dividing each quantity by  $L$  (the galaxy size):  $\int (x/L)(y/L)(dx/L) = (1/L^3) \int y dx$ . The discrete form must therefore be

$$w = \frac{\Delta}{L^3} \sum_i x_i y_i \quad (1)$$

where  $\Delta$  is the pixel size. This definition is valid for any chosen unit. In particular, if we take the pixel as unity, so that  $\Delta = 1$ , we define the warp parameter as

$$w = \frac{1}{L^3} \sum_i x_i y_i \quad (2)$$

The absolute value of  $w$  is a measurement of the degree of warping, and the sign of  $w$  distinguishes between N-like and S-like warps.

Sometimes the warp of a disc is not completely symmetric, and then this parameter would hide the information of the clearly warped side of the galaxy. To avoid this problem we also define the warp parameters on each side of the galaxy independently. Therefore, the right warp parameter is defined as:

$$w_r = \frac{1}{4L_r^3} \sum_{x_i \geq 0} x_i y_i \quad (3)$$

measuring  $x_i$  and  $y_i$  in pixels.  $L_r = \max(x_i)$  is the size of the right side of the galaxy. Similarly, the left warp parameter is defined as:

$$w_l = \frac{1}{4L_l^3} \sum_{x_i \leq 0} x_i y_i \quad (4)$$

measuring  $x_i$  and  $y_i$  in pixels.  $L_l = \max(-x_i)$  is the size of the left side of the galaxy.

With this parameter we can, for example, compare the warp of a galaxy at several wavelengths to determine whether or not a colour gradient exists within the warp. We can also, with the help of this parameter, detect warps that would otherwise have been undetected.

We also propose some parameters which account for these macroscopic geometrical features of the warp. To do this we fit each side of the warp curve to the function:

$$y = \begin{cases} 0 & |x| < |A| \\ C \left( |x - A| - B \left( 1 - e^{-\frac{|x-A|}{B}} \right) \right) & |x| \geq |A| \end{cases} \quad (5)$$

This function reproduces the shape of a warp, i. e., it is flat up to a point and then deviates from the symmetry plane until it reaches an asymptotic direction. The interpretation of the parameters  $A$ ,  $B$  and  $C$  is as follows:

- .-  $A$  is the starting point of the warp.  $A$  has dimensions of length.
- .-  $B$  is the characteristic length in which the warp reaches the asymptotic direction.  $B$  has dimensions of length.
- .-  $C$  is the value of the asymptotic slope.  $C$  is adimensional.

It has been observed in some galaxies that the warp begins in a given direction, and then turns back to the mean plane and ends in the opposite hemisphere. Part of this effect may be due to the fact that the line of nodes and the line of sight do not coincide. Or it may be due to the existence of a more warped dust lane. Or it may be due to an intrinsic effect and indicate a real property of warps. For such galaxies a four-parametric fitting would have been better. But an excessive number of fitting parameters makes the interpretation of simple warps unclear, and we have preferred a three-parametric fitting.

### 3. The software: WIG

We have developed specific software (WIG) to calculate the warp curve and the previously defined parameters form the image of an edge-on galaxy. In the rest of this section we briefly describe how the software works.

WIG has been made to work with nearly centred galaxies in horizontal position (i. e. the major axis of the galaxy approximately coincides with the  $x$  axis and the centre of the galaxy is the centre of the image) as input. Therefore any image must be preprocessed by any standard package in order to fulfill this requirement.

The first step that WIG takes is the calculation of the centre  $(x_0, y_0)$  and the size of the galaxy  $(\sigma_x, \sigma_y)$  (the centre should already be close to the centre of the image as stated before, but this step calculates it more precisely). To do this we use two alternative methods. An iterative gaussian fitting is the choice when the centre of the galaxy has the maximum emission (as happens with optical images); otherwise, a mean value equally weighted for all the points with an emission over one standard deviation of the sky noise is the choice (we term this method *Homogeneous Signal Minus Noise* (HSMN)). (During this step the software also calculates an estimation of the size of the galaxy  $(\sigma_x, \sigma_y)$  which is the width of the gaussians in the first case and the standard deviations in the second one). Once this has been achieved, we select the image zone within  $([x_0 - 3\sigma_x, x_0 + 3\sigma_x], [y_0 - 4\sigma_y, y_0 + 4\sigma_y])$ .

The next step is to erase the stars in the selected zone. This step is a necessary one, because foreground stars lying close to the galaxy can be brighter than it (especially in the peripheral zone in which we are

*Figure 1.* Images of PGC 29691 before (top) and after (bottom) the star deleting process.

particularly interested), and therefore can lead us to erroneous results. An example of this effect is shown at the top of figure (1).

The method chosen for this step has been as follows: We scan each row in the selected zone and by means of a gaussian fit look for peaks exceeding at least two standard deviations the mean sky noise. If the FWHM of the peak is less than a limit value (which we fix at 5 pixels), the pixels around the peak (a FWHM on each side) are substituted by the noise value in that zone. This method has two main advantages over the traditional two-dimensional fitting: first, this method is better at preserving vertical gradients in the zone close to the galaxy, and, furthermore, it is computationally more efficient, because we have less parameters in the fit. The result of this process is shown at the bottom of figure (1).

The next step is the calculation of the warp curve. We need to calculate the *centres* of the galaxy in the direction perpendicular to its symmetry plane. This is the crucial step in the whole process,

and therefore we should be especially cautious. Again, two alternative methods are proposed for this purpose:

.- Gaussian fit: We fit each column in the selected zone to a gaussian. The peak position gives us the *centre* we are looking for, but the FWHM will also be used afterwards.

.- *Shorth*: We select, for each column, the shortest interval containing a given percentage of the data (we have used a value of 40% but other values around 50% lead to equivalent results), and then we calculate the mean position of the peak and its standard deviation in this interval.

Once this step is completed we have not yet finished, because many of the columns belong to the sky background, and not to the galaxy. We have, therefore, to select, among all the columns, those belonging to the galaxy. To do this we scan the columns from left to right and in the opposite direction, and choose the columns fulfilling the following requirements:

- 1) The peak exceeds by at least one standard deviation the sky noise.
- 2) The FWHM of the peak is smaller than  $3\sigma_y$ .
- 3) The change in the peak position from one column to the next is smaller than  $\sigma_y$ .
- 4) The change in the FWHM of the peak from one column to the next is smaller than  $\sigma_y$ .

In the left to right scan, once we have marked  $\sigma_x$  or more columns as belonging to the galaxy, the first column which does not fulfill the requirements marks the right side of the galaxy. The same procedure in the opposite direction marks the left side of the galaxy.

At this point we almost have the warp curve, but another step is still necessary. The reason for this is that we must be sure that the axes in the warp curve are the right ones, i.e. that the  $x$  axis coincides with the symmetry plane of the inner disc and the  $y$  axis with the spin axis of the galaxy. This is a crucial point, because slight deviations from this situation would lead us to erroneous results. To be sure this condition holds we fit the inner part of the warp curve (the pixels in the interval  $[x_0 - \frac{3}{4}\sigma_x, x_0 + \frac{3}{4}\sigma_x]$ ) to a straight line, and then we rotate the warp curve the angle indicated by the slope of this line. Moreover, the value of the ordinate at the origin is taken as the new coordinate of the centre ( $y_0$ ). This is the last step in the process of calculating the warp curve, and now we are ready to start the calculation of the previously defined parameters. This calculation is straightforward from their definition and therefore does not need any comment.

Although in most cases WIG gives good results, there are a few cases in which it has problems. These are the cases of low inclination galaxies in which the spiral arms dominate the geometrical aspect, discs with a

marked dust lane, and images in which a large object is very close to the galaxy under study.

The value of the lower inclination angle for which the method is valid is an essential parameter. Though this number is difficult to estimate, our experience shows that for angles over about  $80^\circ$  the method gives reliable results.

Even though the method is limited to very edge-on galaxies (e.g. inclinations higher than  $80^\circ$ ), this limitation still keeps a rather large sample available which is enough for a statistical study. In any case this new method constitutes a sensible improvement with respect to the subjective method, which has already given good results for optical data.

#### 4. WIG at work: Some examples

Three examples have been chosen to illustrate the usefulness of this software and the parameters: an image in the optical, an image in 21 cm and an image in 1.2 mm.

The first example will be the galaxy ESO 235-53 using the recent data from de Grijs (1997) in the I-band. In this case, several large foreground stars should be masked by hand before using the image as input for WIG. We use the shorth method to calculate the warp curve (which is shown in figure (2) superimposed to a contour map of the galaxy). Before calculating the parameters, the final warp curve has some regions which were linearly interpolated to avoid the effects of the masks for the stars. This will slightly affect the final results specially for the right part of the galaxy.

With this curve we calculate the warp parameters. The results are:

$$\begin{aligned}
 w &= 0.0054 \\
 w_r &= 0.0043 \\
 w_l &= 0.0069 \\
 A_r &= 3.4 \text{ kpc} \\
 B_r &= 16.4 \text{ kpc} \\
 C_r &= 0.175 \\
 A_l &= -15.3 \text{ kpc} \\
 B_l &= 2.4 \text{ kpc} \\
 C_l &= 0.223
 \end{aligned}$$

Now, we show the results of WIG for the galaxy NGC 4013 from the 21 cm data obtained from Bottema (1995). This galaxy is an excellent

*Figure 2.* Warp curve for galaxy ESO 235-53 superimposed to a contour map of the galaxy. The big circles inside the galaxy belong to the areas which were masked out to avoid foreground stars.

one to study warps, because it has an inclination angle of  $90^\circ$  and the line of nodes coincides with the line of sight. The warp of this galaxy has been extensively studied in the optical by Florido et al. (1991). The first step is again to prepare the galaxy to be used as input for WIG (i.e. to put it in a horizontal position). Now we will use the HSMN as the method for calculating the centre (because now the centre of the galaxy is not the brightest part, and therefore a gaussian fit would not be appropriate), and the gaussian fit for calculating the warp curve. The resulting warp curve, superimposed onto the 21 cm image is shown in figure (3)

The warp parameters calculated for this case are:

$$\begin{aligned} w &= -0.0228 \\ w_r &= -0.0232 \\ w_l &= -0.0225 \end{aligned}$$

Figure 3. Image of NGC 4013 in 21 cm with its warp curve superimposed.

$$\begin{aligned}
 A_r &= 6.07 \text{ kpc} \\
 B_r &= 3.20 \text{ kpc} \\
 C_r &= -1.144 \\
 A_l &= -7.90 \text{ kpc} \\
 B_l &= 1.75 \text{ kpc} \\
 C_l &= -0.599
 \end{aligned}$$

This galaxy is extraordinarily warped as can be seen from the value of the parameter  $w$ , and its warp is very symmetric, as shown by the similarity between the parameters  $w_r$  and  $w_l$ . This galaxy is, moreover, a singular one, because its warp in the optical and in 21 cm points in opposite directions.

Finally we show an example in the millimetre range, using for this the recent continuum 1.2 mm data for NGC 4565 from Neininger et al. (1995). We again choose the HSMN method for the centre and the gaussian fit for the warp curve. The warp curve superimposed onto the contour levels of the image is shown in figure (4)

*Figure 4.* Contour levels for NGC 4565 in 1.2 mm with its warp curve superimposed.

In this figure we see that the right side of the galaxy is clearly warped (as can also be seen from the calculated parameters). This effect is also clear in 21 cm, but not so in the optical image (see Neininger et al. (1995)), so this looks as if it there is a colour gradient within the warp.

The warp parameters calculated for this case are:

$$\begin{aligned} w &= 0.00188 \\ w_r &= 0.00389 \\ w_l &= 0.000212 \end{aligned}$$

## 5. Conclusions

We present here a new tool for the statistical study of geometrical properties of warps. First we define new geometrical parameters which account for the size and generic shape of the warp, and we then develop a software which is able to calculate the warp curve and these parameters from the image of a galaxy. We have shown several examples at different wavelengths in order to test the behaviour of both the software and the parameters. These parameters are seen to be a useful tool in detecting some of the effects predicted by the different theoretical models ( colour gradients, coherent alignment of warps, etc...). This will allow to perform a statistical analysis with a large number of galaxies, that could be a key factor in understanding the warp phenomenon. For

example, if we limit such a study to spiral galaxies with inclination higher than  $80^\circ$  (for which the method is certainly valid), a diameter higher than 1.5 arcmin and a total magnitude lower than 15 mag, the available sample contains 288 galaxies (according to the Lyon Meudon Extraalactic Database), which is a sample large enough to allow a statistical study.

The small sample of galaxies considered here shows that the *warp parameter*  $w$  indeed represents the quantitative degree of deformation. One of the galaxies known to be more warped, NGC 4013, has  $w \simeq 0.023$ . Values much greater than this are not to be expected. It is expected that most warped galaxies have a value of  $w$  around 0.01.

The value of the fitting parameters, and in particular the position at which the warp begins and the asymptotic slope, are parameters whose mean value and standard deviation could impose constraints to the different theoretical models, and which inform us about the physical properties in regions external to the disc, either about the dark halo or about the extragalactic medium.

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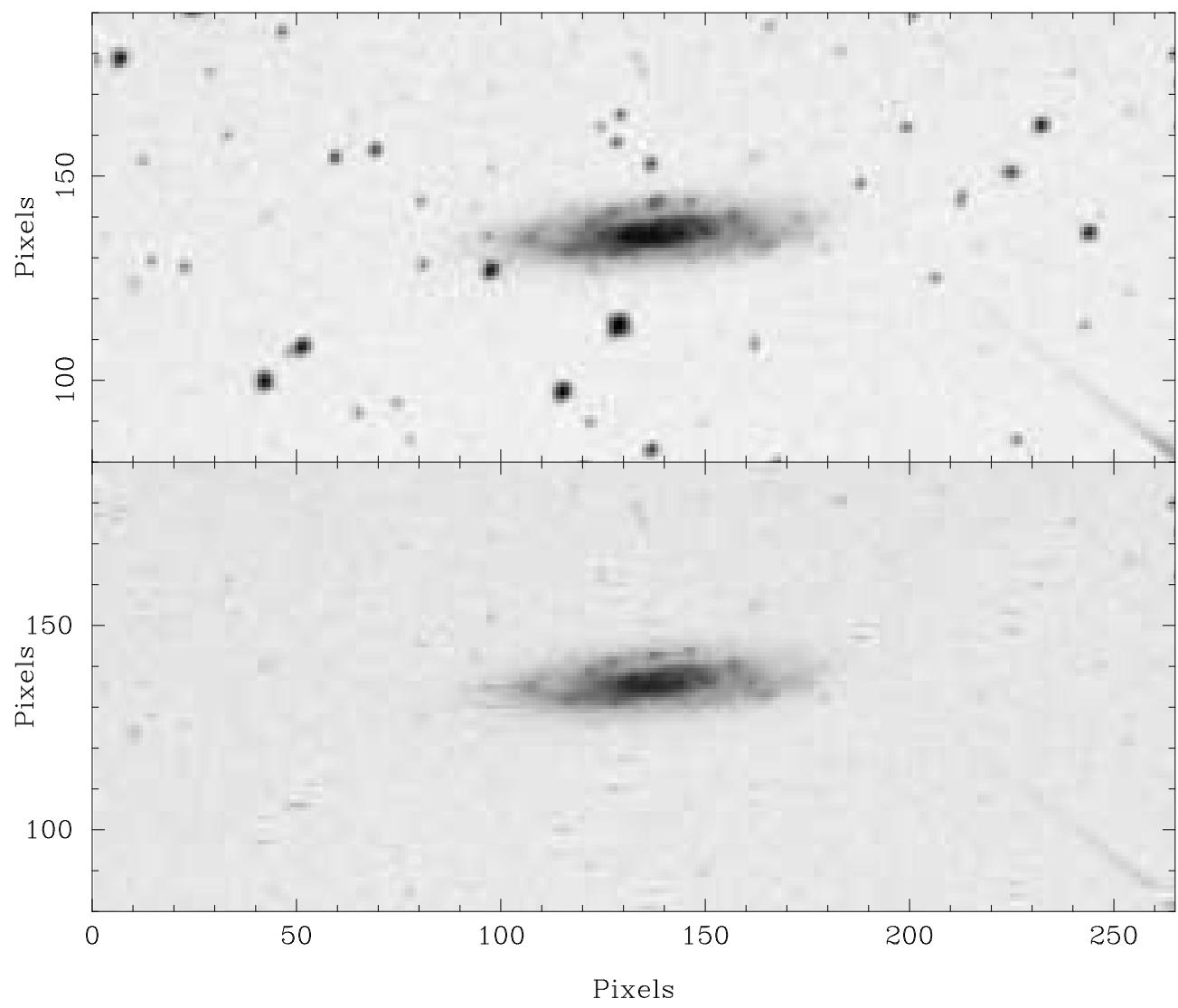
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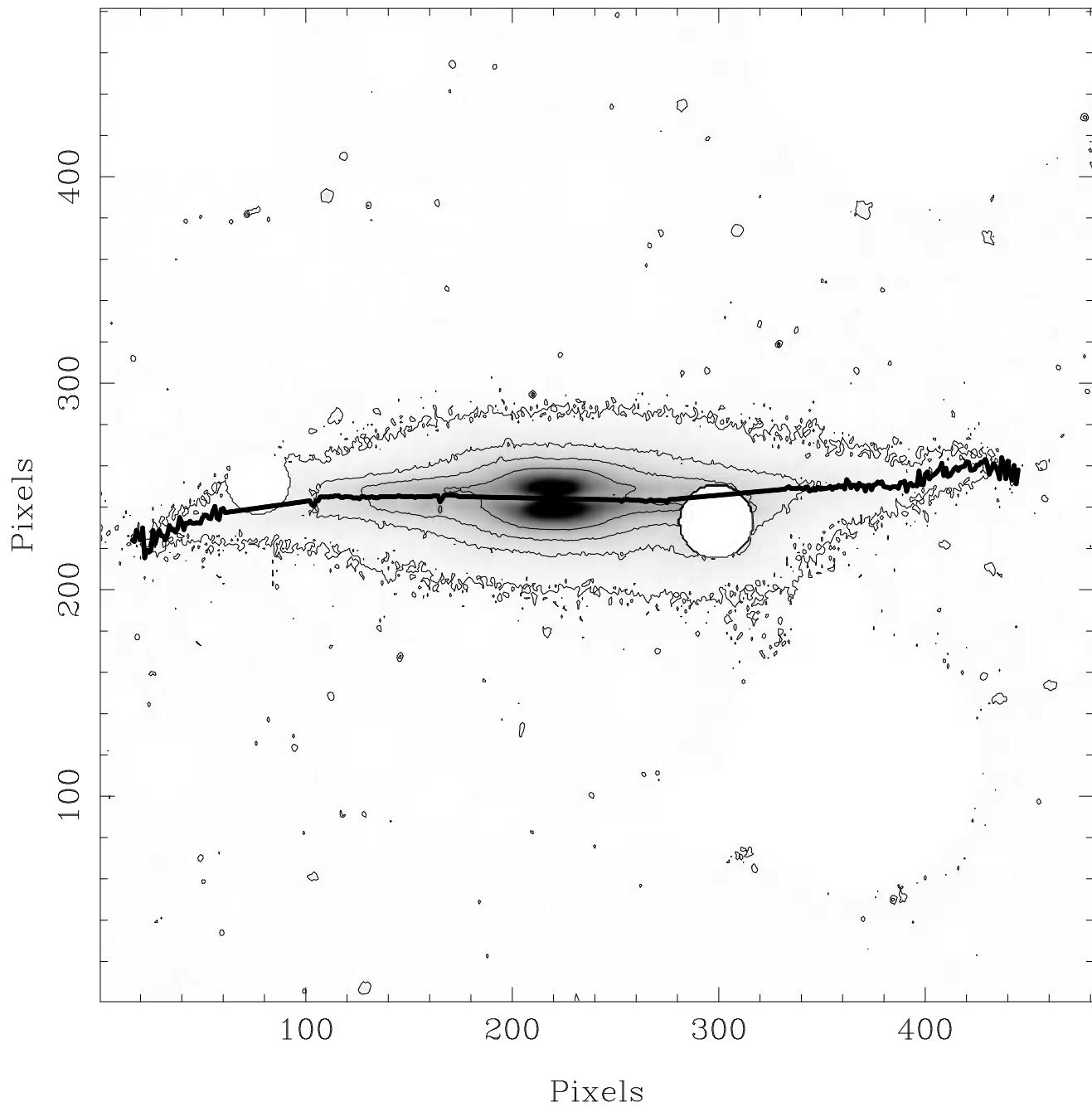
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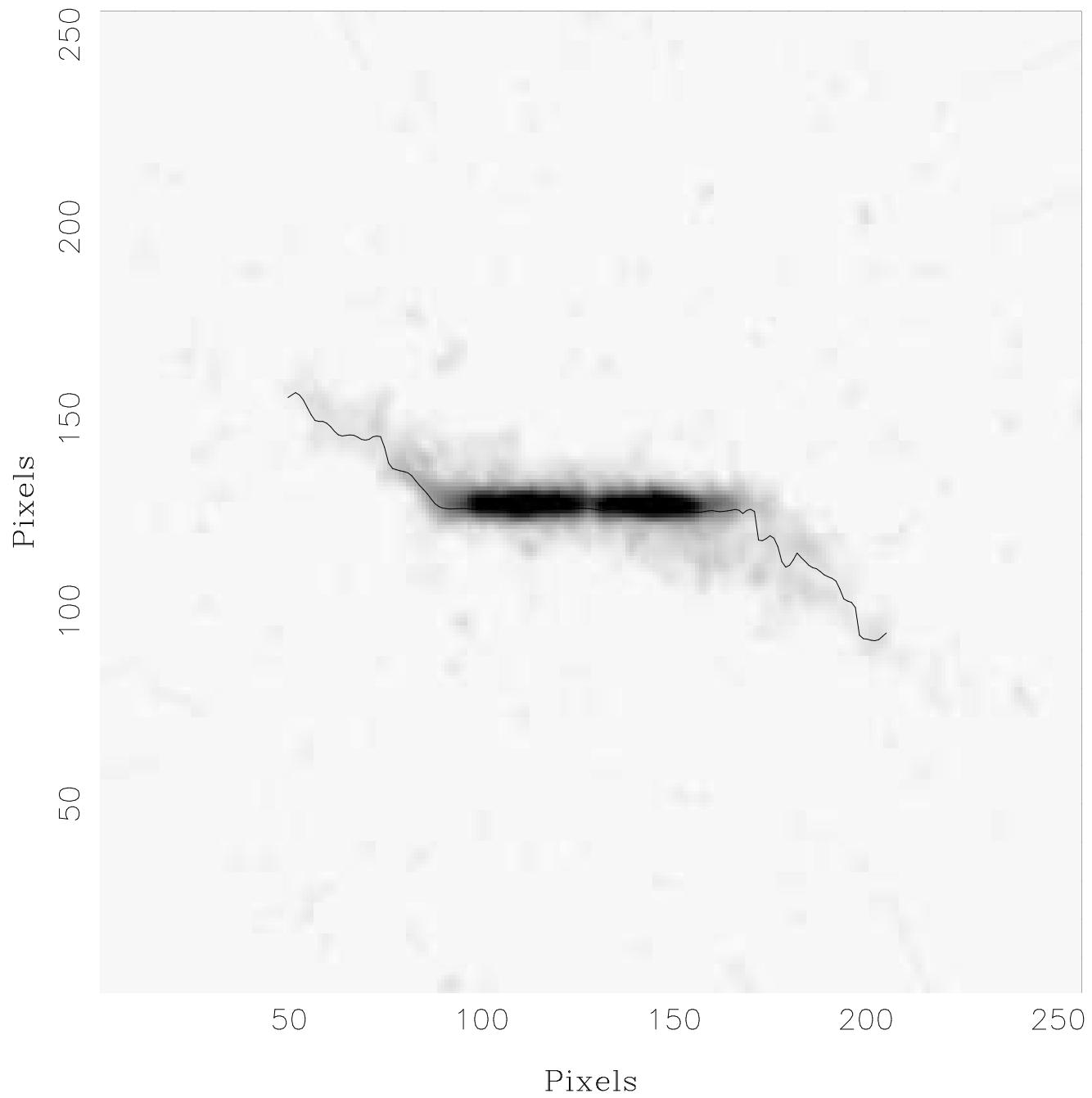
PGC 29691



Galaxy ESO 235-53



Galaxy NGC 4013



Galaxy NGC 4565

